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DEVELOPMENT OF A BRUSH SEALS PROGRAM LEADING TO CERAMIC BRUSH SEALS

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SUMMARY

Some events of a U.S. Army/NASA Lewis Research Center brush seals program are reviewed, and the development of ceramic brush seals is described. Some preliminary room-temperature flow data are given, and the results of testing metallic brushes in cryogenic nitrogen are discussed.

INTRODUCTION

Recognizing the remarkable brush seal accomplishments of John Ferguson of Rolls Royce (ref. 1) and Ralph Flower of Cross Mfg. Ltd. (ref. 2), figure 1, NASA Lewis Research Center embarked on a program to develop the fundamentals characterizing the flow and dynamics of brush seals. The program entailed

1. Developing a heuristic brush seal bulk flow model and code for determining the flow and pressure drop in brush seal systems that would be suitable for both designers and researchers

2. Fabricating simulated brush seal sections with Lucite bristles

3. Utilizing an existing water tunnel facility and fabricating an experimental oil tunnel facility to visualize flows through simulated brush seal sections

4. Setting up an approach for determining rub characteristics, debris, bristle flexure cycles, and seal life associated with long-term operations for the brush seal and rub runner as a system (tribopairing)

5. Integrating observations from an airflow tunnel of the flow through sequences of nylon bristle brushes, such as bristle flexure, flutter, edge loss, and clearance leakage

Toward this end, a bulk flow model and computer code were developed. The model centered on the forces acting on a single bristle and the flow through a porous medium consisting of fibrous materials. Although the details of the brush are proprietary, estimates of its dimensions and allowances for multiple bristles and packing were made and input into the model. By using one data point from Cross Mfg. Ltd., the geometric and flow parameters were established, and predictions of flow and pressure drop followed as illustrated in figure 2.

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A simulated brush seal section with Lucite bristles was fabricated and placed into a water tunnel at NASA Lewis. The flow was seeded with magnesium oxide particles and illuminated with a sheet of laser light. The light provided two-dimensional slices of the flow, revealing a complexity not envisioned (fig. 3). By moving the light beam, the tunnel was surveyed to show flows along the bristles and up and down through the bristles, revealing complex vortex attachments and surface boundary layers. Videotapes of these flow fields were made to illustrate the complexity of brush seal flows (ref. 3).

The program went unsupported by NASA but found support from the U.S. Army Office for further modeling and flow visualization work at the University of Akron. At that time industry and universities were invited to use the program materials, the models, and the limited flow visualization work that was available to begin or supplement their own brush seals programs.

By using the flow visualization methods of Braun et al. (ref. 4), a special oil tunnel was fabricated as well as sets of simulated brush seal sections with Lucite bristles. Because the refraction indices of the Lucite and the oil were matched, these sections could not be seen once they were immersed in the oil, but the magnesium oxide flow tracers illuminated by a sheet of laser light provided two-dimensional slices of flows through the sections that were recorded on videotape. Frame-grabbing techniques and software developed by Braun et al. (refs. 4 and 5) were used to quantify these flows (figs. 4 to 6).

The simple brush seal bulk flow model and code evolved into more complex forms, including extensions to other gases by using the theory of corresponding states. The code still required geometric information and one data point to determine the flow and pressure drop (refs. 6 and 7, fig. 7). Concurrently, a numerical method was developed to characterize the two-dimensional flow patterns about sets of pins simulating flow patterns in brush seals. The code has been validated experimentally and faithfully reproduced the flow patterns associated with a variety of two-dimensional arrays of pins (figs. 8 and 9, refs. 8 and 9).

DEVELOPMENT OF CERAMIC BRUSH SEALS

Testing and modeling brush seal systems (e.g., refs. 10 to 12) including flow, thermal effects, and rubbing effects and projecting the sealing needs of future propulsion systems revealed the need for seals that can withstand high surface speeds and temperatures. Therefore, a brush seal made of silicon carbide bristles and metallic plates and an aluminum oxide brush seal were to be developed. The former is anticipated to operate at 1200 ft/s and 1500 °F and is suitable for configurations now in the design stage. The latter is anticipated to operate at over 1500 ft/s and over 2000 °F and can be used in the next generation of engines. Both types could be used in static sealing applications (ref. 13).

With the assistance of Ralph Flower of Cross Mfg. Ltd., Mel Mitnik of Textron Specialties Co. (silicon carbide fibers), and Saphikon (aluminum oxide fibers), sample brush sections were fabricated and assessed. Although sample brush sections of both silicon carbide and aluminum oxide appeared feasible, NASA Lewis and the U.S. Army Office contracted with Cross Mfg. Ltd. to fabricate the silicon carbide bristle/metallic plate brush seal and to investigate an all-ceramic configuration using aluminum oxide (or other ceramics) with washers of lesser purity purchased from Coors Ceramics to facilitate bristle attachment.

The craftsmanship of the 5.1-in.-diameter silicon carbide bristle/metallic plate brush seal fabricated and delivered by Cross Mfg. Ltd. in February 1992 was superb. Each bristle appeared to be well manufactured and to be placed as well as any metallic bristle with tips ground to a perfect contour to provide the standard 5-mil interference (figs. 10 to 12). Truly a remarkable achievement.

The silicon carbide bristle/metallic plate brush seal was installed for flow testing. At first the rotor could be turned in only one direction. After operation it could be rotated by hand in either direction but rotated freely in one direction only. Upon reinstallation the rotor tended to buckle the bristles, implying that some third-body surface lubrication or preferential surface texturing had developed during operation. The flow rate data at ambient temperatures were consistent (figs. 13 and 14) considering that a brush seal is not a positive seal system and leaks like a porous medium. However, brush seals leak less than labyrinth seals and are dynamically stable (refs. 11 and 14).

Concurrently, a Small Business Innovative Research program was begun by the U.S. Army Office with Technetics Corp. of Deland, Florida, to develop both the silicon carbide/metallic plate and all-ceramic aluminum oxide brush seals (ref. 15). Three fibers were considered feasible: silicon carbide (Textron Specialties), aluminum oxide (Saphikon), and quartz (Dolan Jenner). The layup of the bristles appeared standard, but the braze materials to withstand 1500 °F while not completely wetting the bristles required characterization. Active metal hydrides were effective and the assembly was fabricated into a brush seal capable of 1600 °F operations. The processes are described in reference 15. The progress on the aluminum oxide all-ceramic brush seal was impeded by problems of material instability, excessive shrinkage, and residual stresses. Nevertheless, a methodology for fabricating such a brush seal that centered around a prefired ceramic body with bristle inserts appears able to withstand thermal loads to 2000 °F at high surface speeds.

CRYOGENIC TESTING OF METALLIC BRUSH SEALS

Concurrently, NASA Lewis began an effort to test metallic bristle brush seal systems at cryogenic temperatures under a cooperative agreement with Rocketdyne (ref. 16) in order to determine the feasibility of running brush seals in high-speed turbomachines. The liquid nitrogen flow data were predominantly two phase at the exit and difficult to assess although an initial effort has been described in reference 17 (see also errata). The post-test inspection of the yttria-stabilized-zirconia (YSZ)-coated rub runner and the metallic bristle brush showed them to be pristine (figs. 15 and 16).

OTHER MODELING EFFORTS

In addition to the modeling already cited, several other researchers have developed models to correlate and interpret brush seal flow data. These models also require heuristic information, and many follow the geometric considerations and modeling of the NASA models. In some cases the design methods are characterized, but the details for application are absent (refs. 18 and 19). In other cases the results are simply related to a flow coefficient (ref. 20), and in others they are related to geometric packing (ref. 21) and provide a simple code methodology. Other flexure models (ref. 22) follow the NASA bristle loading model. Still others have provided some results for geometric variations (ref. 23) or for other types of ceramic configurations, such as fiberglass (ref. 24). Although these models and the NASA models provide physical insight into brush seal flow characteristics, the Ergun porous flow model (with modifications for brush seals) could be used to correlate and predict brush seal flows with simplicity (fig. 17). Two data points would be required to establish geometric and flow parameters, and the gaseous results for simple corresponding-states fluids appear to fit quite well. The effects of surface speed are not well established.

$$\Delta P = a\left(\frac{\mu}{\mu_0}\right)\dot{V} + b\left(\frac{\rho}{\rho_0}\right)\dot{V}^2$$

Laminar Turbulent

For the seal configuration and data described in reference 7,

$$a = 25\sqrt{M}$$

$$a = 25M \quad \text{For helium}$$

$$b = 0.00015\ M \times F(f_0)$$

where

ΔP	pressure drop, Pa
$\dot{V} = A_0 u_0$	volumetric flow rate at standard conditions (1 bar and 300 K), cm^3/s
A_0	flow area without bristles (shaft to fence), cm^2
u_0	flow velocity in flow area without bristles, cm/s
M	molecular weight of gas
f_0	turbulent friction factor
μ_0	viscosity at reference conditions
ρ_0	density at reference conditions

where the subscript 0 refers to the reference conditions used to evaluate a and b; usually these are standard conditions, such as 1 bar and 300 K.

Note that $\dot{w} = \rho \dot{V}$, the mass flow rate in grams per second, can be used in the relation by substituting for $\dot{V}$; and usually $F(f_0) \rightarrow$ constant = 1 is assumed but has not been verified. Also note that for gaseous helium the linear coefficient becomes proportional to M rather than to $\sqrt{M}$, which also requires verification as helium is a quantum fluid with viscous effects nearly equivalent to those of air.

Ideally, the coefficients a and b are related to brush porosity e, thickness $\langle t \rangle$, and bristle diameter d, with a also related to viscosity μ and b related to density ρ and to the turbulent friction factor f_0.

$$\phi = \frac{\langle t \rangle / d}{e^3}, \quad a = 2\phi\mu/(A_0 d), \quad b = \phi \rho f_0 / A_0^2$$

For geometries other than described in reference 7, coefficients a and b have to be recalculated or ratioed; for example,

$$a = \left[\frac{\frac{\phi\mu}{A_0 d}}{\left(\frac{\phi\mu}{A_0 d}\right)_0}\right] \times \begin{cases} 25\sqrt{M} \\ 25M \end{cases} \quad \text{For helium}$$

$$b = 0.00015\ M \left[\frac{\phi \rho f_0 / A_0^2}{\left(\phi \rho f_0 / A_0^2\right)_0}\right]$$

CONCLUSIONS

Recognizing the propulsion system requirements of next-generation engines, the NASA Lewis Research Center and the U.S. Army Office have successfully developed, fabricated (using two different methodologies), and flow checked a silicon carbide bristle/metallic plate brush seal system.

The success of the brush seals program and the successful operation of brush seals in cryogenic fluids under a cooperative agreement have led to a technology test bed demonstration program for brush seals in high-speed turbomachines.

ACKNOWLEDGMENT

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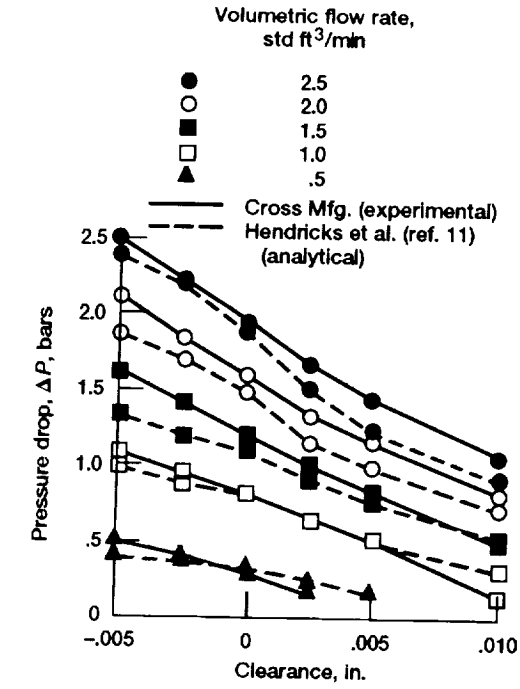
Figure 1.—Circular brush seal. (Courtesy of Cross Mfg. Ltd.)



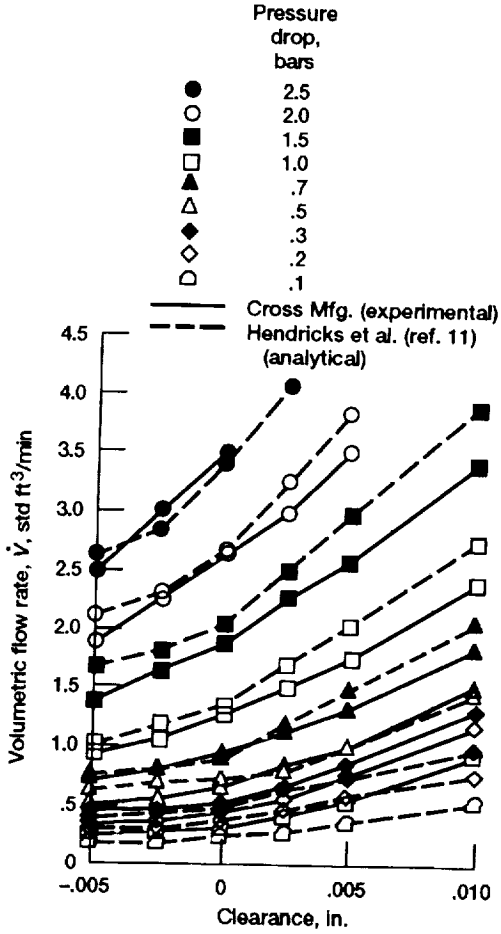
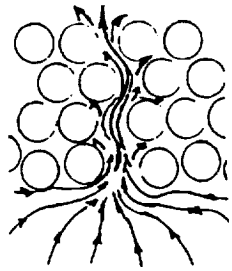
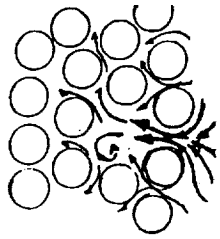


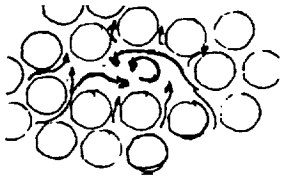
Figure 2.—Comparison of brush seal bulk flow model with experimental data of Cross Mfg. Ltd. Brush seal diameter, 5.1 in.



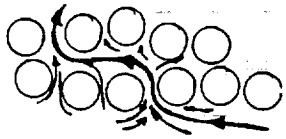
(a) Rivering.



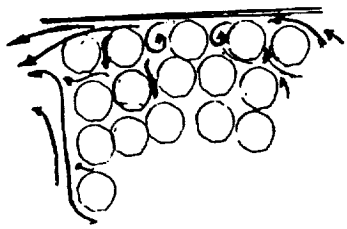
(b) Jetting.



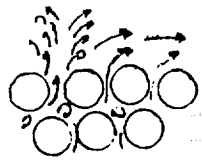
(c) Vortical flow.



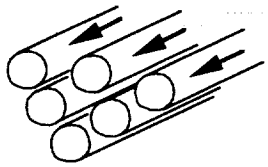
(d) Lateral and parallel flow.



(e) End-wall flow.



(f) Flow at bristle tips.



(g) Radial flow.

Figure 3.—Observed flow patterns in brush seals.

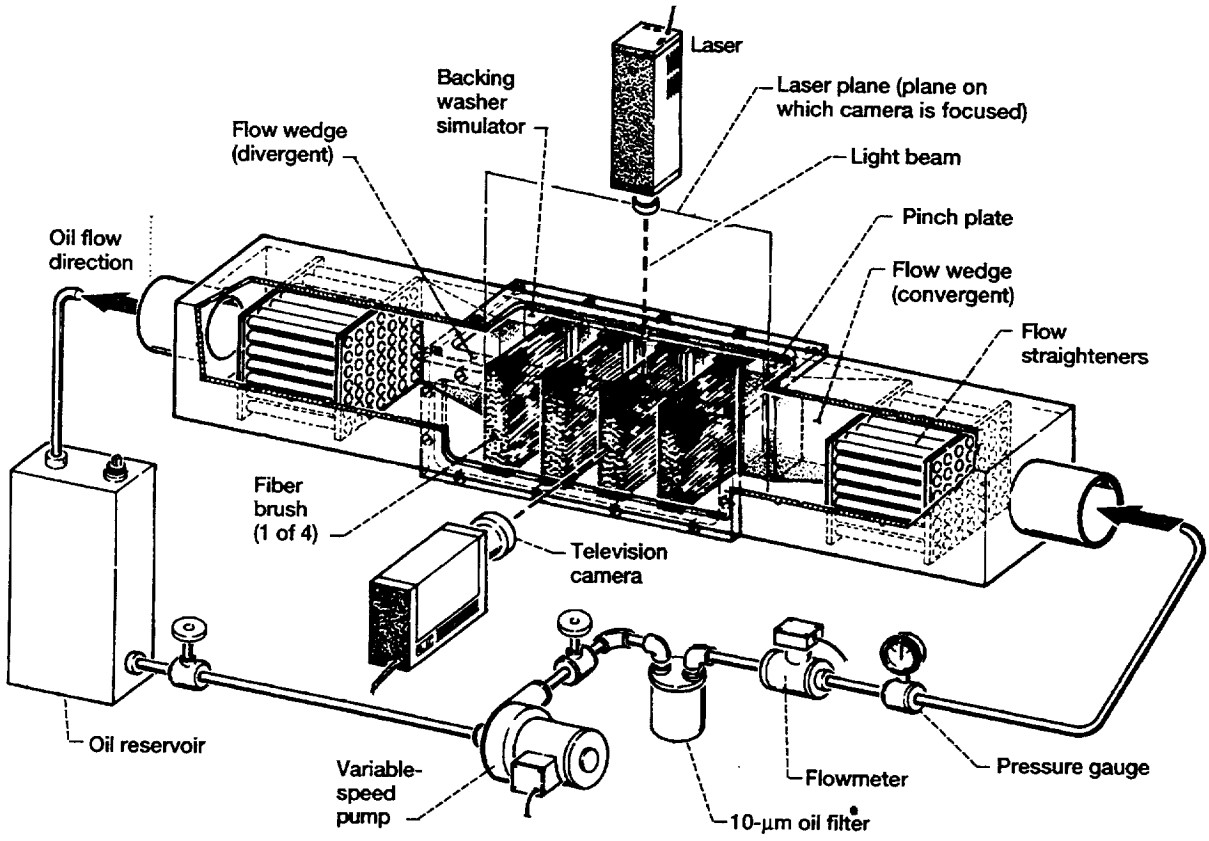
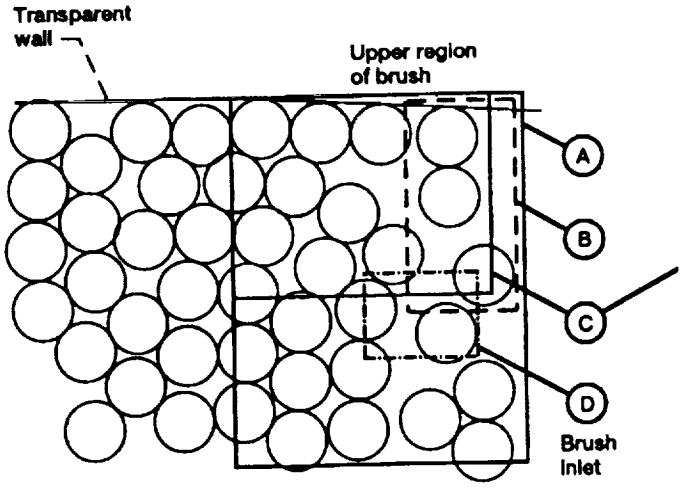
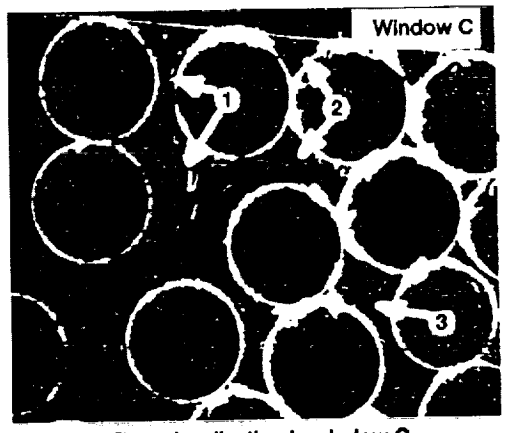


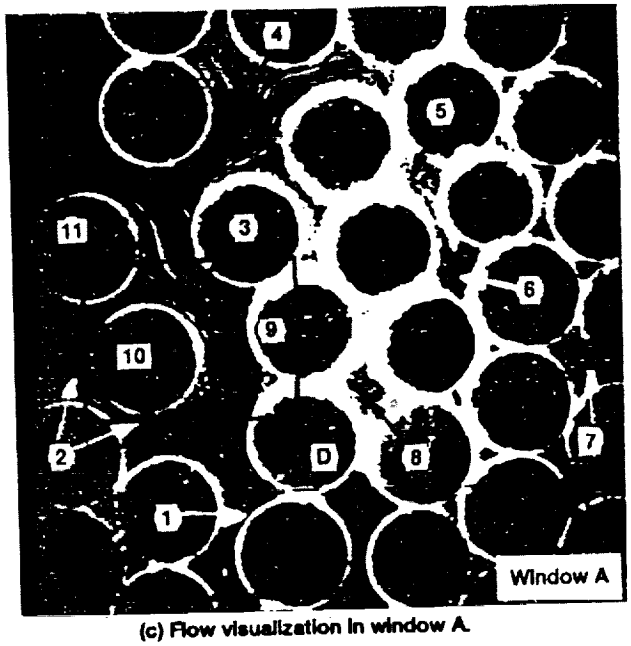
Figure 4.—Two-dimensional oil flow visualization facility.



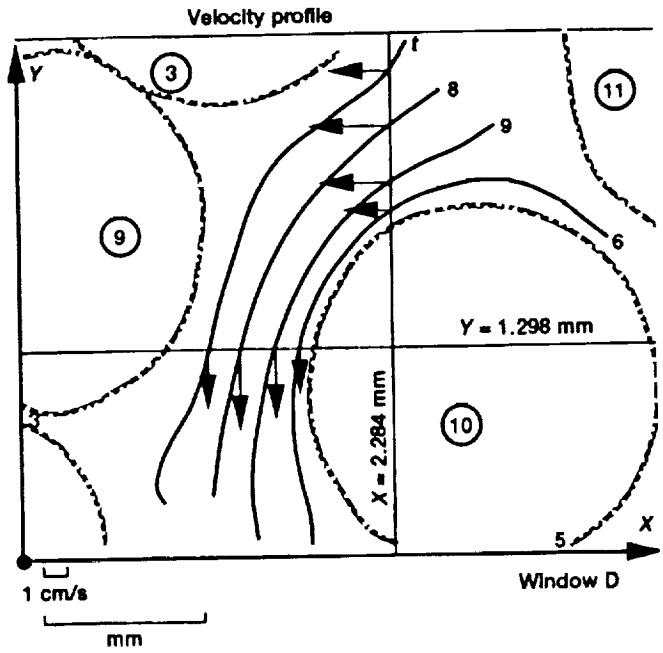
(a) Map of upper region of brush (2-mm bristles).



(b) Flow visualization in window C.



(c) Flow visualization in window A.



(d) Quantification of flow trajectories and velocities in window D.

Figure 5.—Qualitative and quantitative flow assessment in inlet section of brush seal (oil tunnel).

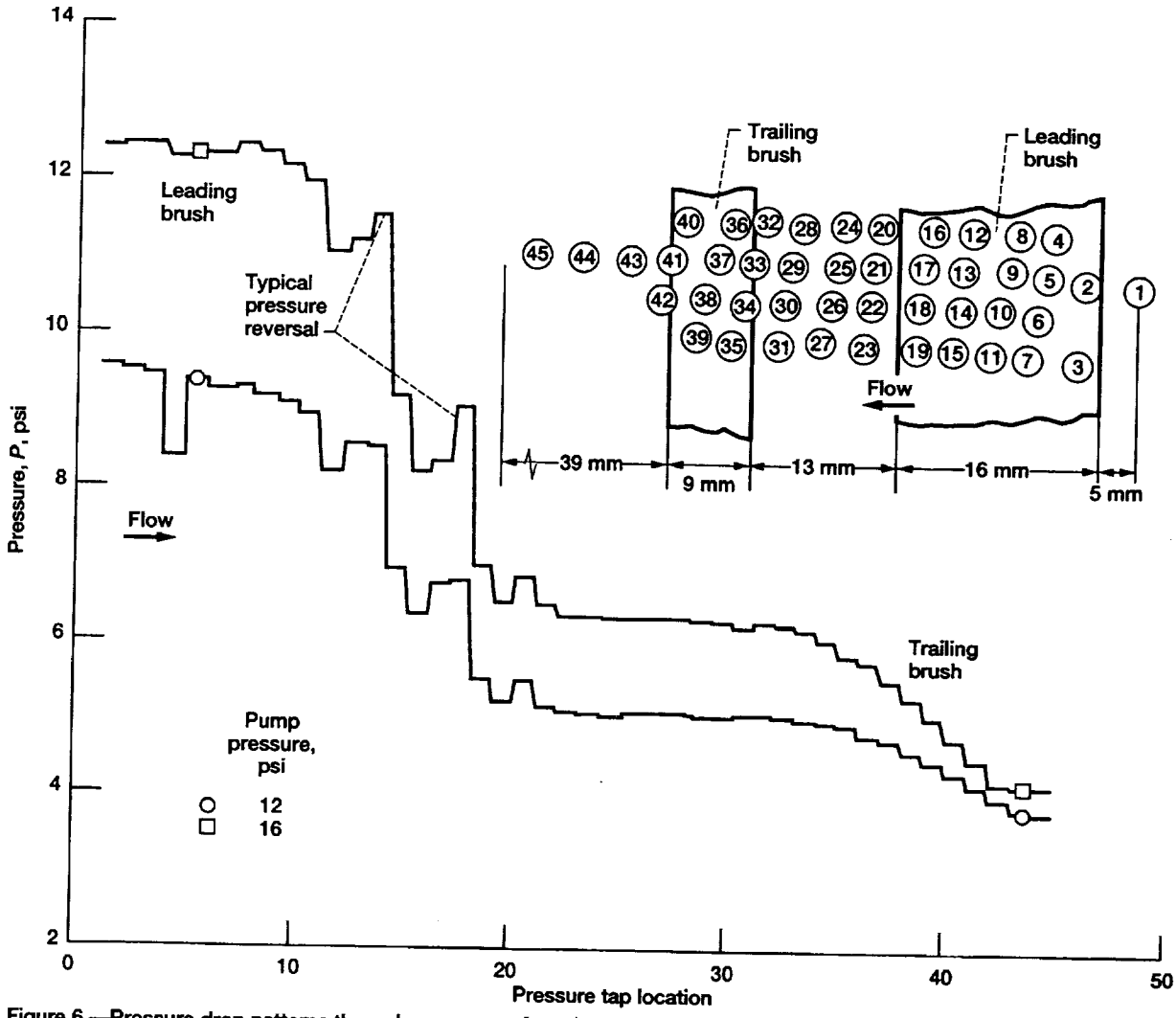


Figure 6.—Pressure drop patterns through sequence of two brushes. Bristle diameter: leading brush, 2 mm; trailing brush, 1 mm.

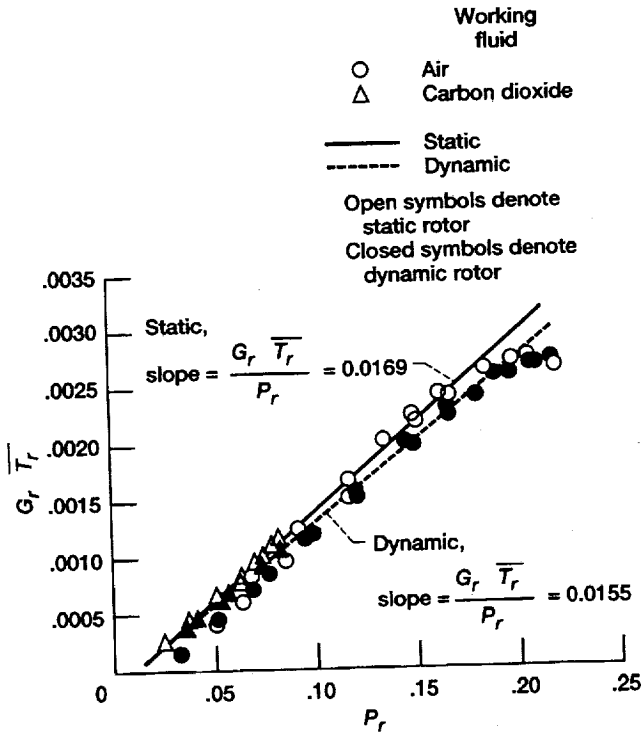
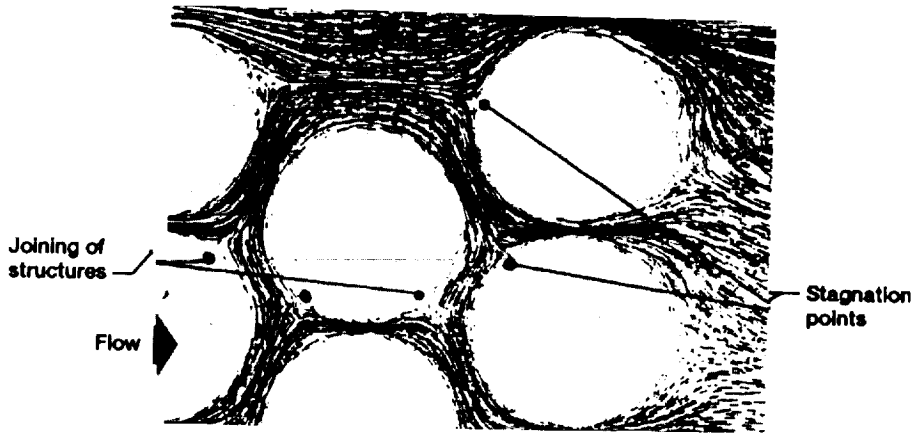
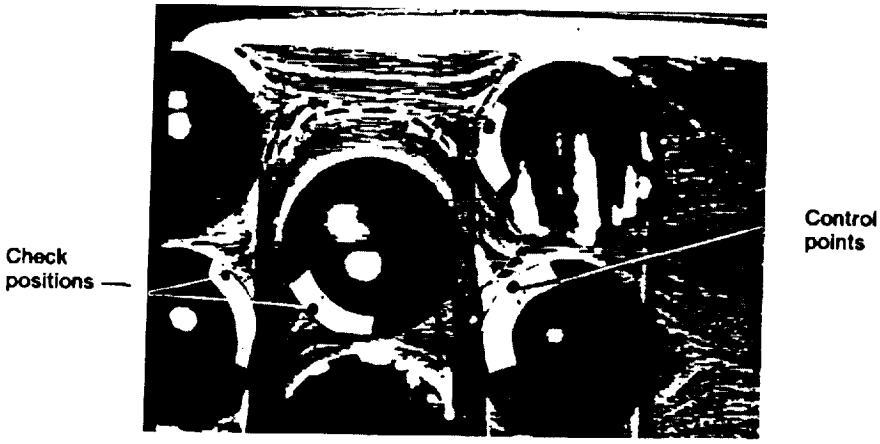


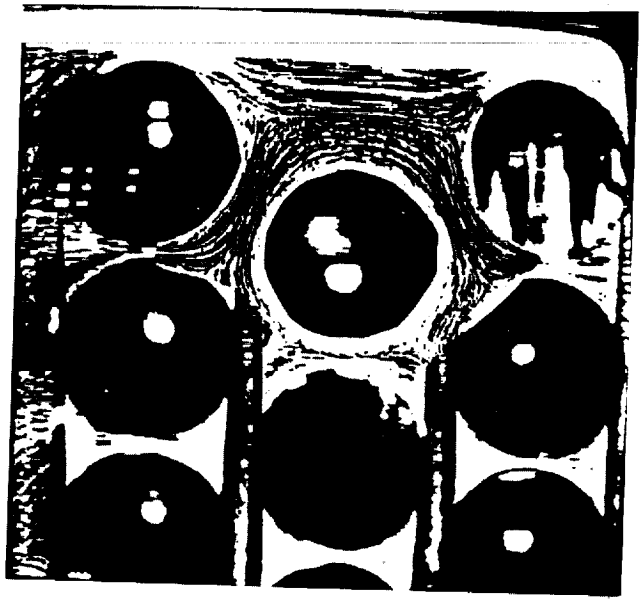
Figure 7.—Normalized brush seal performance data at static and low-speed dynamic rotor conditions in air and carbon dioxide. Radial interference, 0.0024 in. (G_r = reduced mass flux; T_r = reduced temperature; P_r = reduced pressure, P_{in}/P_c, where P_{in} = inlet pressure and P_c = pressure at critical point).



(a) Numerical.

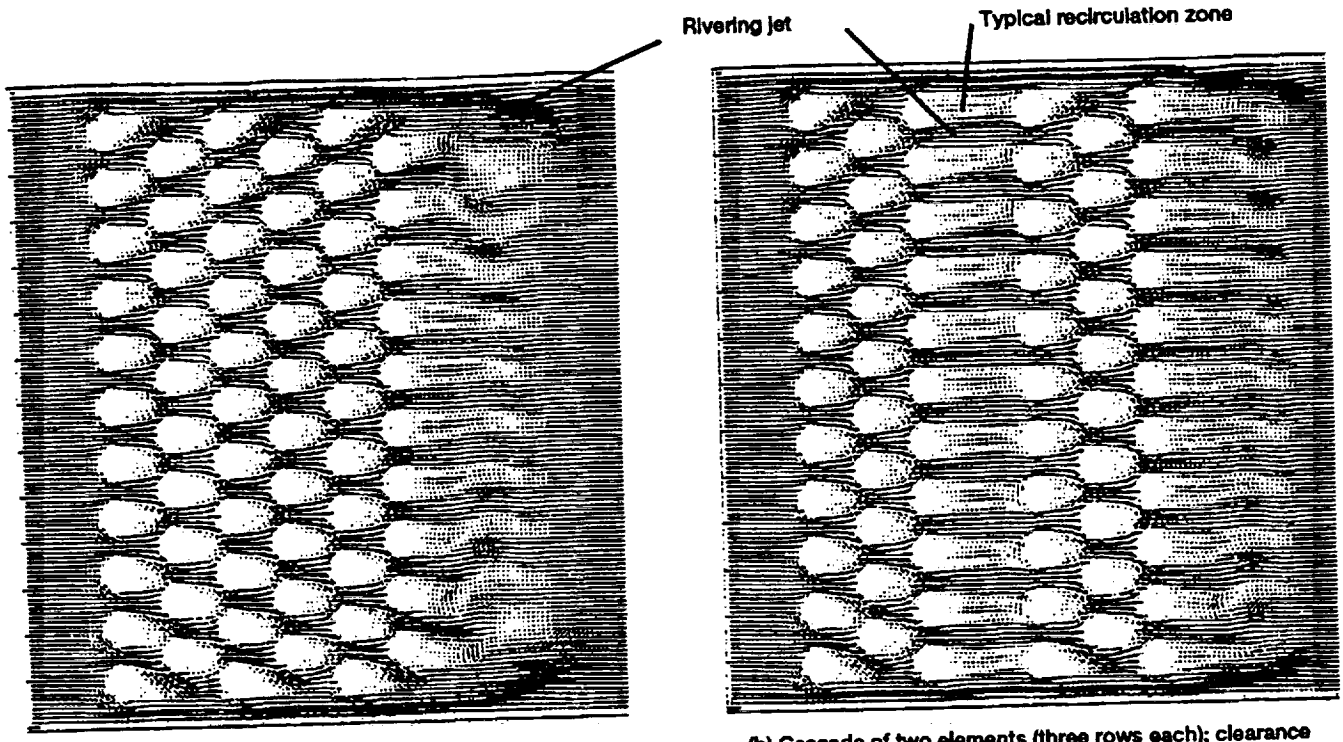


(b) Experimental.



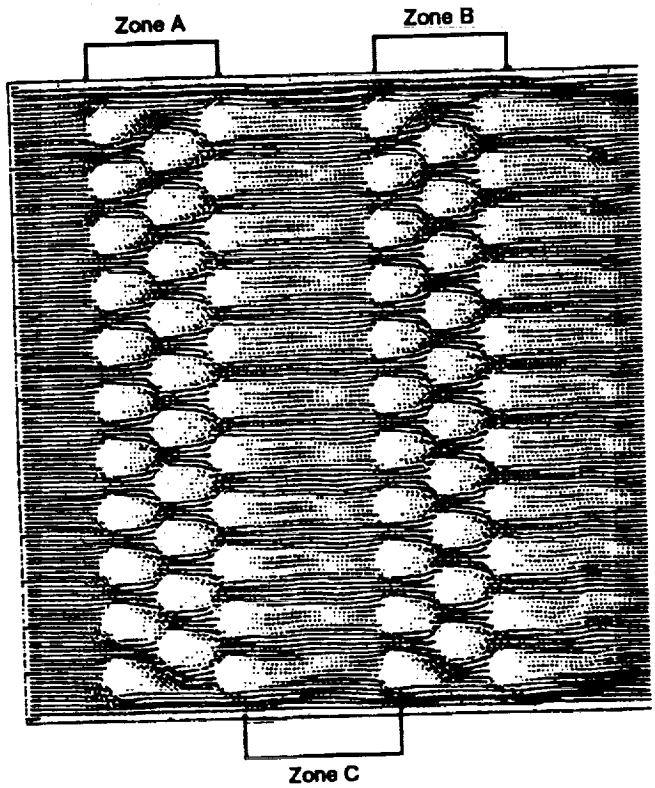
(c) Compositional (a) and (b).

Figure 8.—Comparison of calculated and experimental flow structures in cylindrical arrays of pins.



(a) Six rows.

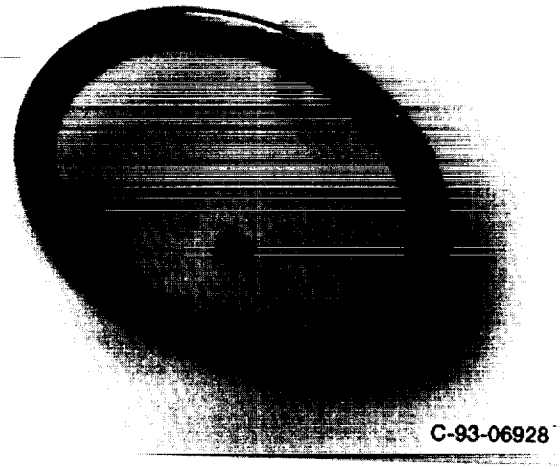
(b) Cascade of two elements (three rows each); clearance spacing, 3 diameters.



(c) Cascade of two elements (three rows each); clearance spacing, 5 diameters.

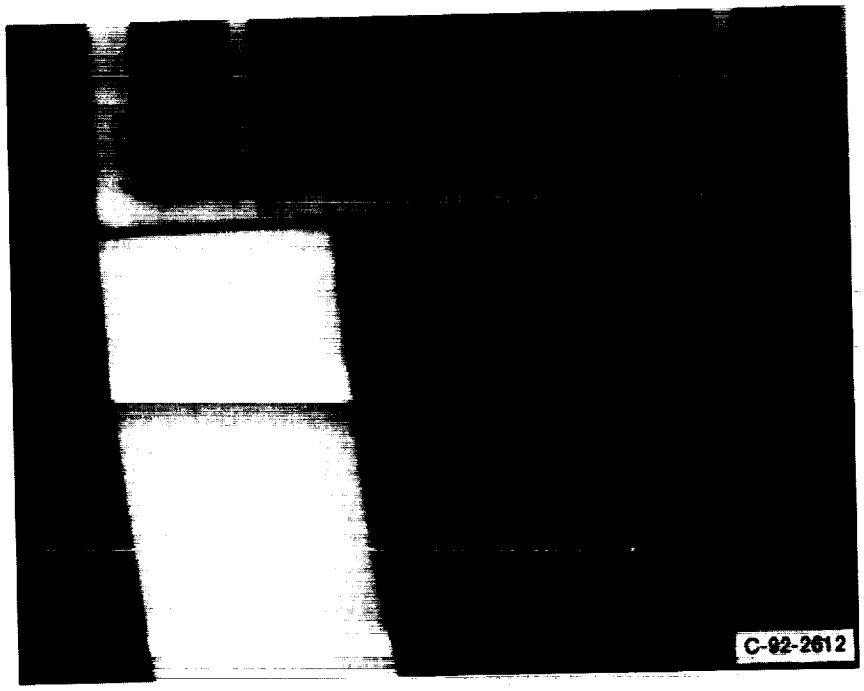
Figure 9.—Calculated flow across cascade of two arrays of cylindrical pins. Reynolds number, 2000.

(a) Plan view.

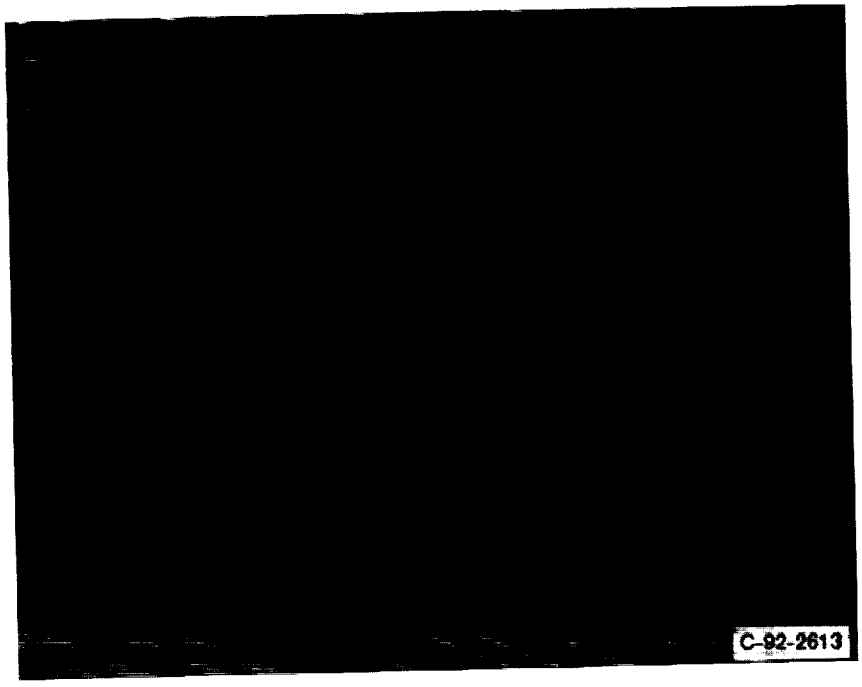


(b) Isometric view.

Figure 10.—Silicon carbide bristle/metallic plate brush seal.

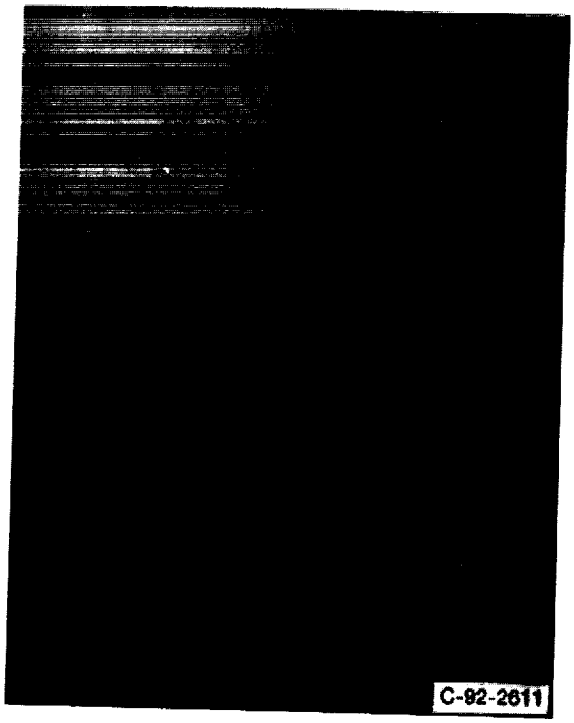


(a) Bristle layup.

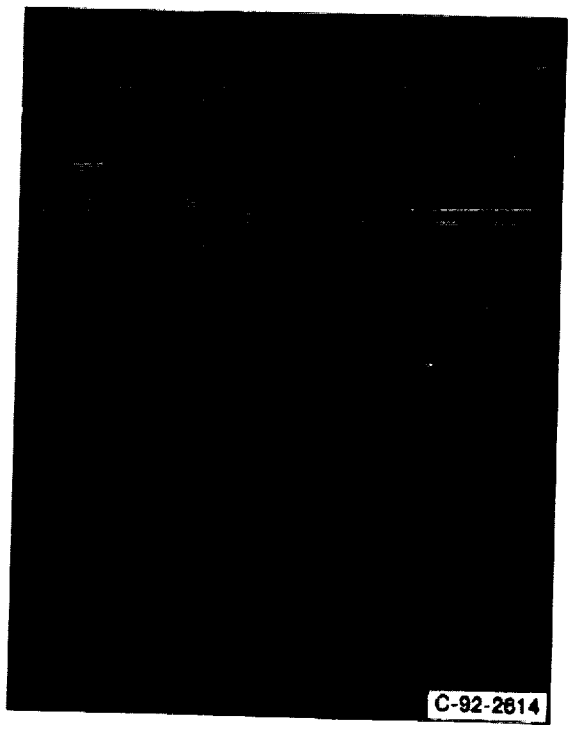


(b) Closeup including bristle tips.

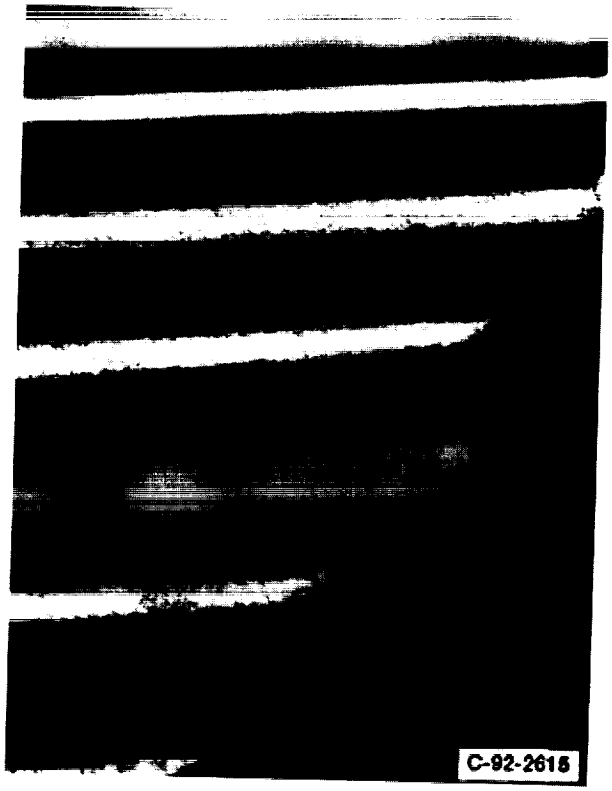
Figure 11.—Details of silicon carbide bristle/metallic plate brush seal configuration.



(a) Cored bristles.



(b) Closeup of bristle tips.



(c) Bristle tip contours.

Figure 12.—Silicon carbide bristle tips.

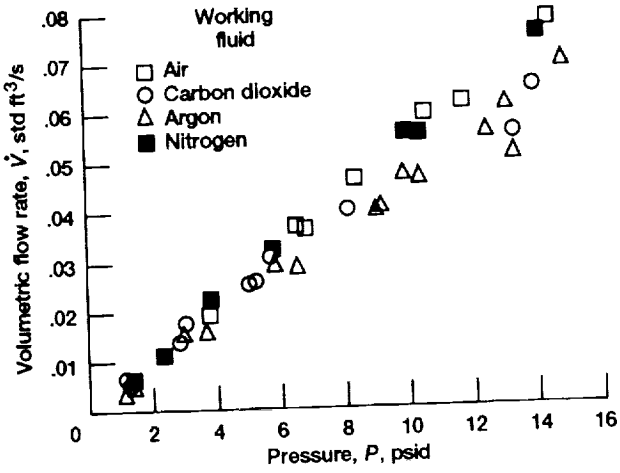


Figure 13.—Flow data for 1.5-in.-diameter silicon carbide bristle/metallic plate brush seal at ambient temperature and 2600 rpm.

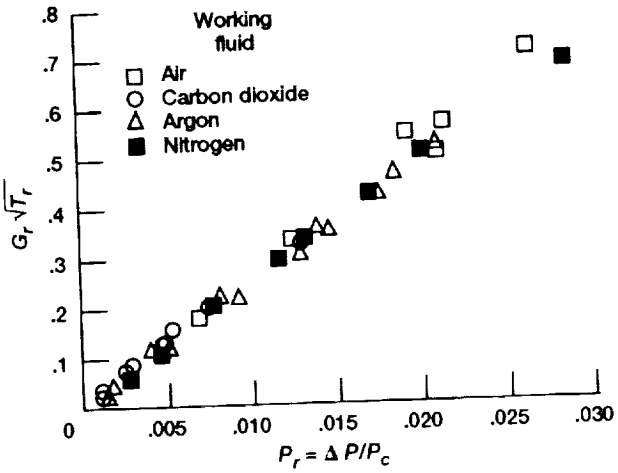
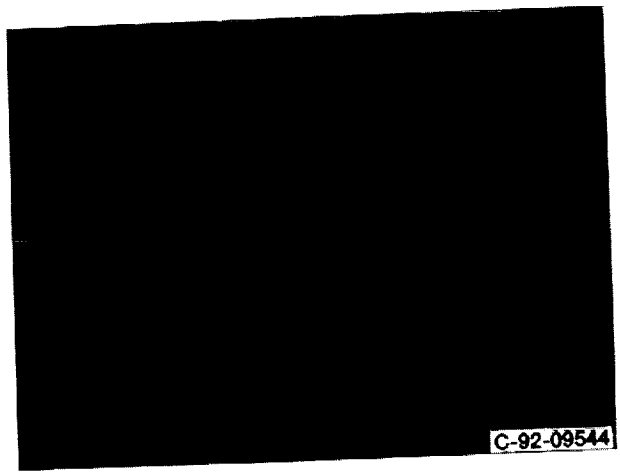
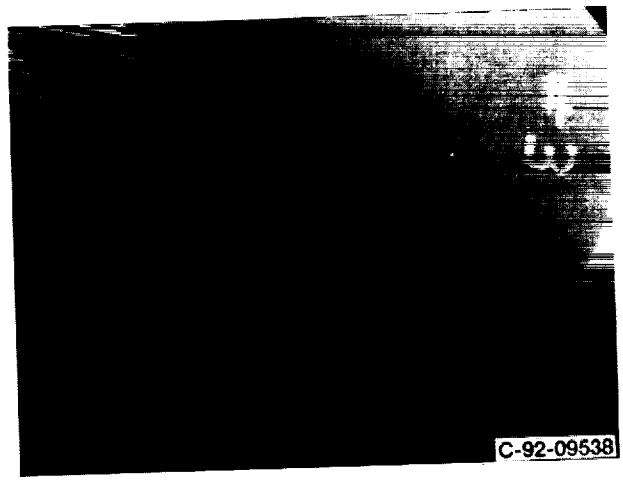


Figure 14.—Normalized flow data for 1.5-in.-diameter silicon carbide bristle/metallic plate brush seal at ambient temperature and 2600 rpm. (See fig. 7 for definition of symbols.)

(a) Upstream side.



(b) Downstream side.



(c) Bristle interface.

Figure 15.—Metallic brush seal (Cross Mfg. Ltd.) and YSZ-coated rub runner (Technetics Corp.)—single brush typical of five-brush configuration.

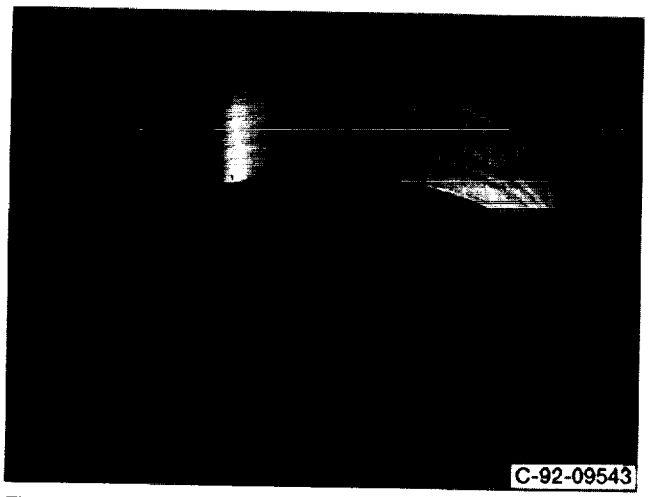


Figure 16.—Post-test photograph of YSZ-coated rub runner from Cross Mfg. Ltd. metallic brush seal, illustrating wear tracks of five-brush configuration.

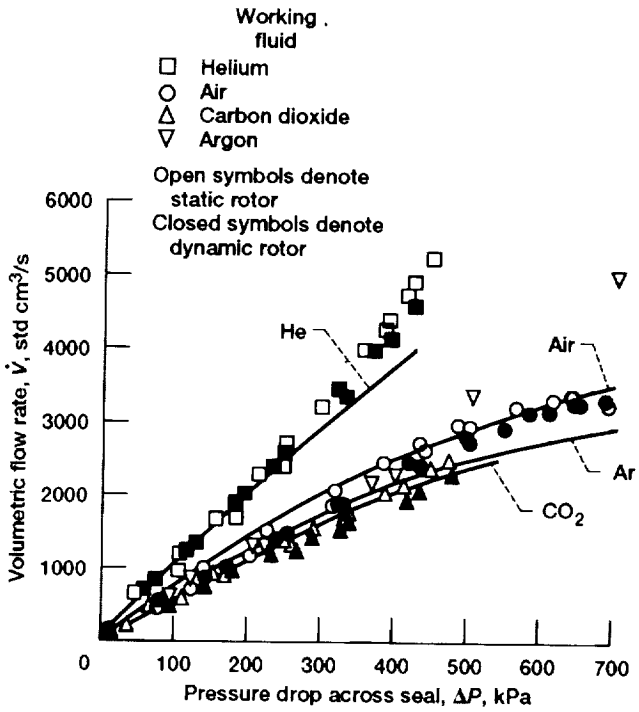


Figure 17.—Simplified brush seal modeling based on Ergun relation, standard volumetric flow rate versus pressure drop across brush seal for gaseous helium, air (or nitrogen or oxygen), argon, and carbon dioxide. $\Delta P = 25\ \overline{M}\ (\mu/\mu_0)\ \dot{V} + 0.00015\ M\ (\rho/\rho_0)\ \dot{V}_2$, where M is molecular weight, μ is viscosity, ρ is density, and subscript zero denotes standard conditions (1 bar, 300 K); for helium use M in place of $\overline{M}$.